

## **2000 Progress Report**

### **1. Principal Investigators and Affiliations**

Graeme L. Stephens, PI  
C. Martin R. Platt, Co-PI  
Department of Atmospheric Science  
Colorado State University  
Fort Collins, CO 80523-1371

### **2. Title of Research Grant**

The use of Lidar/Radiometer (LIRAD) in the ARM Program to obtain optical properties and microphysics of high and midlevel clouds (DE-FG03-98ER62569)

### **3. Scientific goals**

The goal of the project has continued to focus on obtaining optical and microphysical properties of cirrus (and some mid-level clouds) using combinations of lidar and infrared and microwave radiometry. Millimetre radar has also been used in an associated project to extend retrievals to more detailed cloud microphysics. The main work has focussed on tropical cirrus and the continuing analysis and interpretation of data obtained in the Maritime Continent Thunderstorm Experiment (MCTEX). The goal has been to retrieve information on the microphysics of very cold tropical clouds and the general optical properties of such clouds.

A second goal is the continued development and future use of fast, sensitive, narrow-beam filter radiometers for lidar/radiometer (LIRAD) applications at ARM CART sites and in associated experiments. Specifically, a radiometer has been developed that can operate over long periods with minimal attention for use initially at the SGP ARM CART site. It is planned that such a radiometer design should play an important part in the future ARM plans of retrieving cloud properties remotely.

An associated goal is to develop methods for the rapid semi-automatic analysis of lidar and radiometer cloud data from ARM CART sites in near real-time. This has involved an extension of the basic LIRAD methods.

### **4. Summary of chief accomplishments**

- Development of a new parameterisation of the IR absorption coefficient of tropical cirrus clouds from LIRAD data.
- Final retrieval of effective radii of high cold tropical cirrus from lidar/radiometer methods using theory developed by D. Mitchell.

- Discovery of, and explanation for, strong cooling at the base of tropical storm anvils advected away from the original convective area.
- Three papers have been written and submitted for publication on the MCTEX data.
- The CSIRO/ARM Mark II Infrared Radiometer has been checked out and prepared for operation at the SGP ARM CART site.

## 5. Progress and accomplishments during the past twelve months

### 5.1 Final analysis of MCTEX results

Considerable time was spent on the final MCTEX analysis, including careful assessments of uncertainties. Such assessments were the basis for statements on levels of confidence of the various retrievals. The analyses were repeated during the year following new information on the water vapour radiance behaviour and its variation with time. Several new discoveries were made as a result of the analysis that gives us new insights into cirrus properties and evolution. Three papers on these results were written and submitted for publication (Platt et al. 2000a, b, c). The various results and their interpretation are described in more detail below.

#### *a. General optical and microphysical properties of tropical cirrus*

The work over the past year was a continuation of past work in the project during the 1997-1998 period. During that period, optical properties of tropical cirrus were retrieved with the LIRAD analysis and compared with previous experiments.

In the past year, the data were analysed again with a better parameterisation of the measured water vapor path and its variations. This was necessary to better remove the effects of variations in water vapor path that can be as large as the cirrus radiance being measured. The dependence of absorption coefficient  $\sigma_a$  on temperature was found to be different compared to that in mid-latitudes, but rather similar to that obtained at the ARM Pilot Radiation Observation Experiment (PROBE) at an equatorial site (Platt et al. 1998). Using this information, a final parameterisation has been developed over the past year that relates infrared spectral absorption coefficient  $\sigma_a$  to mid-cloud temperature. Although it is found that there is considerable scatter in these values in any temperature interval, the average of a number of values give a consistent variation with temperature.

A similar refinement to the values of the effective backscatter-to-extinction ratio  $k/2\eta$  was made with the re-analysis of the data. A similar dependence was found on temperature as before. Theoretical values of  $\eta$  similar to those used previously in PROBE were used to calculate  $k$ . Some further theoretical results reported by Macke and

Mischenko (1996), Macke et al. (1996), and Hess et al. (1998) were used to compare with the empirical results. These showed that a distortion of a typical crystal shape in the calculations was necessary to reduce some of the theoretical values of  $k$  to measured values. However, several methods of distortion of the crystal shape by the above authors yielded similar reductions in  $k$  leading to an ambiguity in the results. Tables 4 and 5 of Platt et al. (2000a) show an assortment of theoretical values of  $k$  compared with experimental values. Further theoretical results on depolarisation ratio  $\Delta$  failed to remove the ambiguity. Retrieved values of depolarisation ratio  $\Delta$  showed an increase towards lower temperatures, as found from earlier results. Some results from the above analyses are depicted in Figures 1a to 1c.

The values of  $\sigma_a$  for tropical cirrus are shown plotted against the quantity  $(T_0 + T)$  (where  $T_0 = 82.5^\circ\text{C}$ ) in Figure 2. Also shown is a fit by the function:

$$\sigma_a = A(T + T_0)^2 + B(T + T_0) + C \quad (1)$$

This formula can be used as a parameterisation for tropical cirrus. A previous fit made by Platt and Harshvardhan (1988) on mid-latitude cirrus is also shown. Tropical cirrus is seen to have greater absorption at the lower temperatures.

A similar fit was made to the values of  $k$  shown in Figure 10 of Platt et al. (2000a):

$$k = bT + k_0 \quad (2)$$

Values of  $A$ ,  $B$ ,  $C$ ,  $b$  and  $k_0$  are shown in Table 3 of Platt et al. (2000a), along with regression coefficients,  $R^2$ .

The above results have been submitted for publication in Platt et al. (2000a). They should be useful both for parameterisation of the optical properties of tropical cirrus in terms of temperature and for validation of models of evolution and radiative transfer in tropical cirrus

#### *b. Small particles in high, cold cirrus clouds*

A detailed study of the values of the ratio of visible extinction coefficient to IR absorption coefficient,  $\alpha$ , indicated quite high values at low temperatures, similar to values found in PROBE. Values were binned in ten-degree temperature intervals. The range of values in each bin was then separated out in histogram form. Two such histograms at two temperatures are shown in Figures 3a and 3b, which shows the spread in each interval, with a change in mean value to larger values of  $\alpha$  at the lower temperatures. A plot of mean values of  $\alpha$  in various temperature intervals is shown in Figure 4. Despite the large uncertainties and spread in values, there is a trend to larger values of  $\alpha$  with decreasing temperature.

The above results can be compared with the theoretical calculations of Mitchell and Platt (1999) for different ice crystal habits. Some of Mitchell's results of  $\alpha$  versus effective diameter  $D_e$  are shown in Figure 5. The sensitivity of  $D_e$  to values of  $\alpha$  is seen to be small until  $D_e$  decreases below about 5 microns, below which there is a steep rise in  $\alpha$ . Looking at the data again in Figure 4, it is seen that on average the  $\alpha$  values indicated crystal sizes less than 10 microns at temperatures less than about  $-50^\circ\text{C}$ . These sorts of values have been suggested from recent theory (Jensen et al., 1996). There is a rapid fall-out of larger crystals from storm anvil layers initially, leaving small particles that tend to stay in the upper troposphere for many hours, as observed.

This is the first time that such small particles in cirrus clouds have been detected remotely. Confirmation of the small particles is provided from millimetre radar, where no returns were detected from the cloud layers analysed. The detection threshold of the millimetre radar was considered to be 10 to 20 microns radius. The predominance of small particles in a tropical cirrus cloud would have a profound effect on the cloud optical depth for a given ice water content. Optical depth would increase as the effective radius of the cloud particles decreased. Thus the solar albedo would also increase and any net warming effect due to cirrus clouds would be reduced or nullified.

*c. Observation of strong cooling at anvil cloud base*

Part of the MCTEX aim was to observe thunderstorm anvil clouds with lidar, radiometry and millimetre radar as they drifted over the site and gradually dissipated. A number of thunderstorm anvils did drift over the site from more distant storms, affording the opportunity for a LIRAD analysis of such clouds. The anvils were always very attenuating to lidar pulses originally but eventually broke up to give penetration to cloud top. An interesting feature of the infrared radiance from cloud base was that the emittance calculated from that radiance never increased above 0.8 to 0.9. This was despite the fact that a lidar pulse was attenuated within 1 or 2 km, whereas millimetre radar indicated that the anvil cloud extended to much greater depths. This is illustrated by time-height images of simultaneous lidar backscatter and radar reflectivity as shown in Figures 6a and 6b. The effective lidar cloud depth is only about 2 km, whereas the radar showed a cloud with a much higher cloud top. Generally, a cloud that is fully attenuating to visible light indicates a black cloud in the infrared window region, so that one would assume that the emittance would be close to unity (scattering effects were removed). The emittance corresponding to Figures 6a and 6b is shown in Figure 6c. The emittance commences near unity but then falls as the cloud base falls, finally levelling out at a value of about 0.8, indicating strong cooling at cloud base.

The calculations of emittance were made assuming that adjacent radiosondes (in both space and time) gave the correct anvil cloud temperatures. Thus, the depressed emittance could be interpreted as a cooling below the ambient values near cloud base. The lower measured emittance would correspond to a lower brightness temperature. Cooling of the cloud base was quite likely due to the strong evaporation that must have been occurring as the anvil material fell into sub-saturated air below cloud base. A simple theoretical model of such a case gave order-of-magnitude agreement with cooling values calculated from the depressed emittance. The model assumed that the anvil material was falling into sub-saturated air below cloud base and that the cloud particles were evaporating and moistening the air to saturation.

Calculations of values of measured cooling compared with theoretical values and plotted against cloud base temperature are shown in Figure 7. Results are comparable, although the measured values of cooling tend to be higher. This is probably a reflection of the simple model employed, with no allowance made for further subsidence due to negative buoyancy.

Values agreed also with the cooling calculated from the ice evaporation using millimetre radar reflectivity values. Using the Sekelsky et al. (1999) formula that relates radar reflectivity to ice water content, the cooling for a complete evaporation of the ice water content, corresponding to maximum reflectivity, could be calculated for various values of cloud particle effective radius. The effective radius was also estimated from the lidar backscatter/radar reflectivity ratio near cloud base and found to be comparable.

Similar cases of depressed emittance were discovered when data from a 1981 expedition to Darwin were re-examined and found to show similar effects. Despite periods of high lidar attenuation, the emittance again remained below values of 0.8 to 0.9.

This is the first time that cooling at cloud base has been observed remotely and with such detail. It provides a tool to examine many other cases that may be observed at CART sites, particularly the CART sites at Manus Island and Nauru. These results will appear in Platt et al. (2000c).

## *5.2 Preparations and Transport of the CSIRO/ARM Mark II Narrow Beam, Spectral, Infrared Radiometer for Operation at the SGP CART Site*

The plan is to transport the radiometer from CSIRO in Australia to the Department of Atmospheric Science at Colorado State University, Fort Collins, Colorado around August 2000. From there, the radiometer will be checked out and subsequently taken to the SGP CART site to be installed. Arrangements have been made with U.S. Customs

in Denver to import the radiometer free of duty as it comes under a “spectrometer” category. The radiometer’s Stirling cycle cooler is now three years old and has been sent to the manufacturers, Bel Electronics Inc., in California to be re-gassed and refurbished. It will be installed again in the radiometer either in Australia or in Fort Collins before final installation at the CART site.

The Mark II radiometer has already been checked out at CSIRO this year and found to operate well once some thermistor calibrations had been modified. The radiometer has been fitted with a “hot” blackbody calibration source over the past year. Using an external liquid nitrogen blackbody, and ambient and hot blackbodies, correlation of the radiance signal with temperature was linear with a coefficient better than 0.99. An example is shown in Figure 8. For this calibration an external liquid nitrogen blackbody source was used together with the ambient temperature and “hot” blackbody calibration sources.

During the rest of this year, data will be received at Fort Collins and checked for quality and for stable calibration features. It is hoped also to have some good cases of micropulse lidar and radiometer observations of cirrus clouds to analyse.

### *5.3 Automation of LIRAD analysis method for use at CART sites*

The lidar/radiometer (LIRAD) analysis methods have been modified for semi-automatic, continuous retrieval of cirrus optical properties. The method has been used already to analyse several months of lidar and radiometer data from the Nauru site in the tropical Pacific. Some results from this analysis are shown in Figure 9.

## **Aims for 2001**

It is anticipated that the CSIRO/ARM Mark II Radiometer will be installed and operating at the SGP CART site by the end of the present year’s funding on 30 November. The year 2001 will be taken up by learning how to operate the radiometer, acquiring suitable data and analysing some of the results. The data will be sent electronically to the Department of Atmospheric Science at Colorado State University in Fort Collins for quality control and calibration checks.

Suitable cases of high cloud systems observed by the radiometer and micropulse or Raman lidar will be analysed by the LIRAD method to obtain detailed results on cloud optical properties. The analyses will also employ microwave radiometer data of water vapour path, together with routine radiosonde data. The data will also be used

for comparison and checks of calibration integrity utilising data from the AERI instrument integrated over the radiometer spectral interval.

The radiometer will operate for a period of about six months. By June 2001, sufficient analysed data should have been obtained to fully check the performance of the radiometer. If satisfactory, then the project could be expanded to the other CART sites, particularly the North Slope of Alaska, if agreement is obtained with ARM. The NSA site requires a radiometer that can measure very low levels of water vapor in the atmosphere with very low sky brightness temperatures in the clear sky. The Mark II radiometer should be able to achieve this.

Data from the CART site taken during the six-month period will also be used in reports and possibly a publication.

## References

- Hess, M., R. B. A. Koelemeijer, and P. Stamnes, 1998: Scattering matrices of imperfect hexagonal crystals, *J. Quant. Spectrosc. Radiat. Transfer*, **60**, 301–308.
- Jensen, E. J., O. B. Toon, H. B. Selkirk, J. D. Spinhirne, and M. R. Schoeberl, 1996: On the formation and persistence of subvisible cirrus clouds near the tropical tropopause, *J. Geophys. Res.*, **101**, 21,361–21,375.
- Macke, A., and M. I. Mischenko, 1996: Applicability of regular particle shapes in light scattering calculations for atmospheric ice particles, *Appl. Opt.*, **33**, 4291–4296.
- Macke, A., J. Mueller, and E. Raschke, 1996: Single scattering properties of atmospheric ice crystals, *J. Atmos. Sci.*, **53**, 2813–2825.
- Mitchell, D. L., A. Macke, and Y. Liu, 1996: Modelling cirrus clouds. Part II: Treatment of radiative properties, *J. Atmos. Sci.*, **53**, 2967–2988.
- Mitchell, D. L., and C. M. R. Platt, 1999: Microphysical interpretation of LIRAD extinction/absorption ratios using a microphysics-radiation scheme, *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 23-27, 1998, Tucson, Arizona*, 495–498.
- Platt, C. M. R., A. C. Dilley, J. C. Scott, I. J. Barton, and G. L. Stephens, 1984: Remote sounding of high clouds. V: Infrared properties and structure of tropical thunderstorm anvils, *J. Clim. Appl. Meteor.*, **23**, 1296–1308.
- Platt, C. M. R., J. C. Scott, and A. C. Dilley, 1987: Remote sounding of high clouds. VI: Optical properties of midlatitude and tropical cirrus, *J. Atmos. Sci.*, **44**, 729–747.
- Platt, C. M. R., and Harshvardhan, 1988: Temperature dependence of cirrus extinction: Implications for climate feedback, *J. Geophys. Res.*, **93**, 11,051–11,058.
- Platt, C. M. R., S. A. Young, P. J. Manson, G. R. Patterson, S. C. Marsden, R. T. Austin, and J. Churnside, 1998: The optical properties of equatorial cirrus from observations in the ARM Pilot Radiation Observation Experiment, *J. Atmos. Sci.*, **55**, 1977–1996.
- Platt, C. M. R., S. A. Young, R. T. Austin, and G. R. Patterson, 2000a: LIRAD observations of tropical cirrus clouds in MCTEX. Part I: Optical properties and parameterisation of tropical cirrus, submitted to *J. Atmos. Sci.*

Platt, C. M. R., R. T. Austin, S. A. Young, and D. L. Mitchell, 2000b: LIRAD observations of tropical cirrus clouds in MCTEX. Part II: Detection of small particles in cold cirrus clouds, submitted to *J. Atmos. Sci.*

Platt, C. M. R., R. T. Austin, S. A. Young, and A. J. Heymsfield, 2000c: LIRAD observations of tropical cirrus clouds in MCTEX. Part III: Optical properties and base-cooling in dissipating storm anvil clouds, submitted to *J. Atmos. Sci.*

Sekelsky, S. M., W. L. Ecklund, J. M. Firda, K. S. Gage, and R. E. McIntosh, 1999: Particle size estimation in ice-phase clouds using multi-frequency radar reflectivity measurements at 95 GHz, 33 GHz, and 2.8 GHz, *J. Appl. Meteor.*, **38**, 5–28.

Young, S. A., C. M. R. Platt, R. T. Austin, and G. R. Patterson, 2000: Optical properties and phase of some midlatitude, midlevel clouds in ECLIPS, *J. Appl. Meteor.*, **39**, 135–153.



## 6. Figures

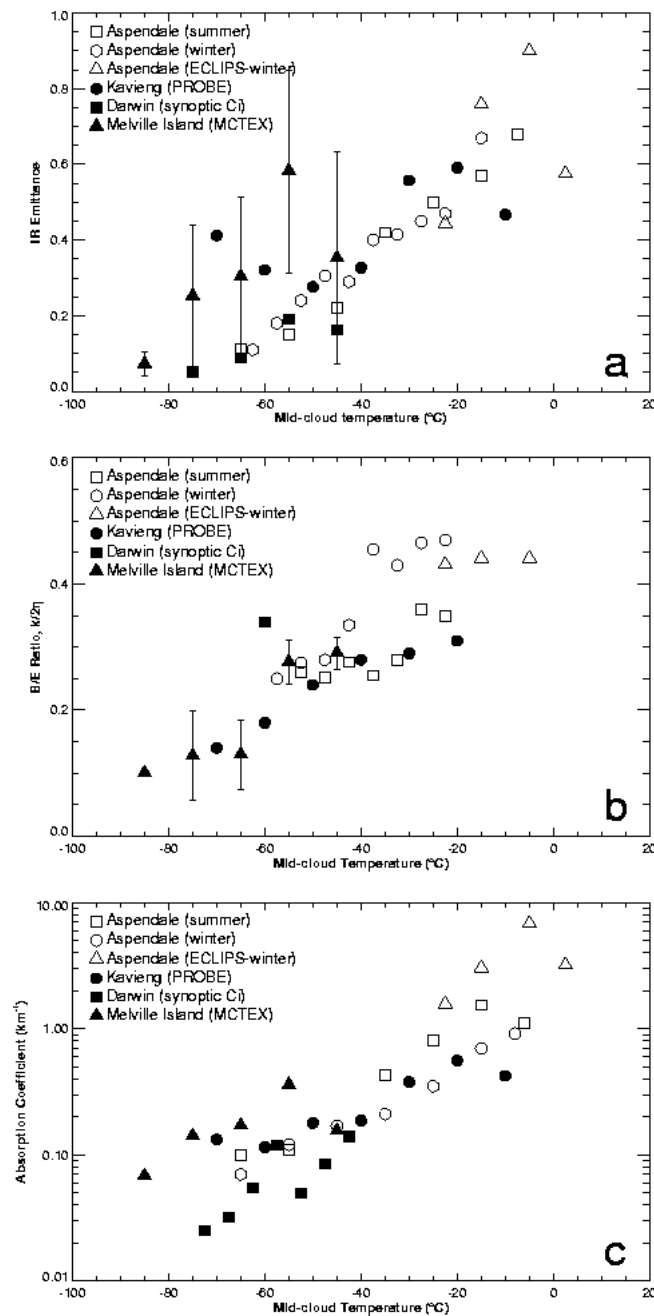


Figure 1. Mean values of (a)  $\epsilon_a$ , (b)  $k/2\eta$ , and (c)  $\sigma_a$  versus temperature for ten-degree temperature intervals.

Aspendale summer and winter refer to Platt et al. (1987); Aspendale ECLIPS to Young et al. (2000); Kavieng PROBE to Platt et al. (1998); Darwin synoptic to Platt et al. (1984). Bars represent the standard deviation in the spread of individual samples.

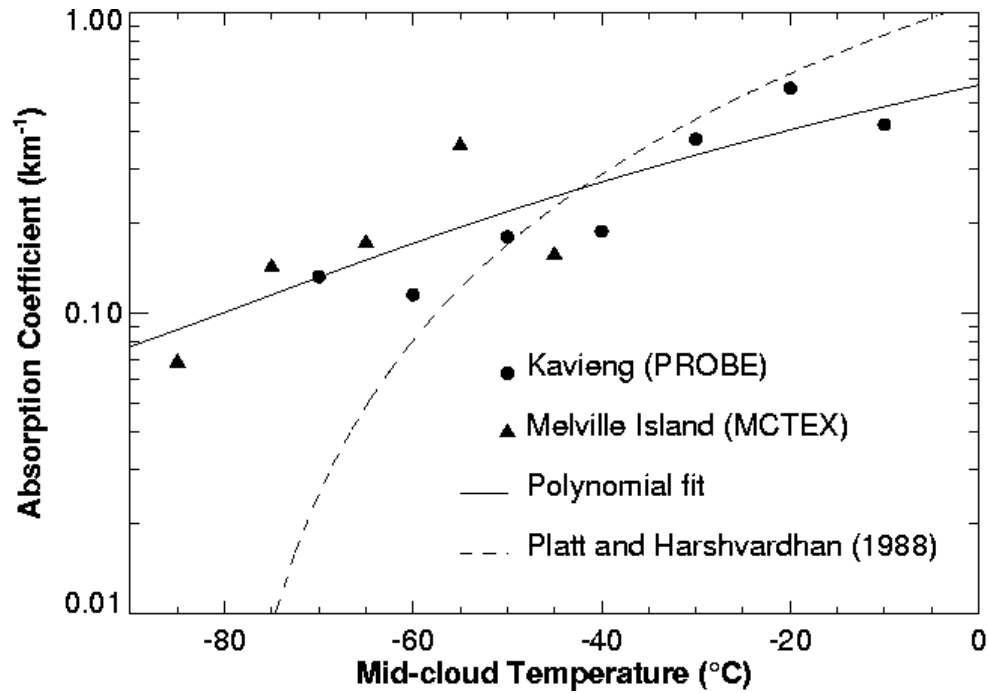


Figure 2. Mean values of  $\sigma_a$  versus  $(T + T_0)^2$  for MCTEX and PROBE (Platt et al. 1998) data. The relation of Platt and Harshvardhan (1988) is also shown.  $T_0 = +82.5^{\circ}\text{C}$ .

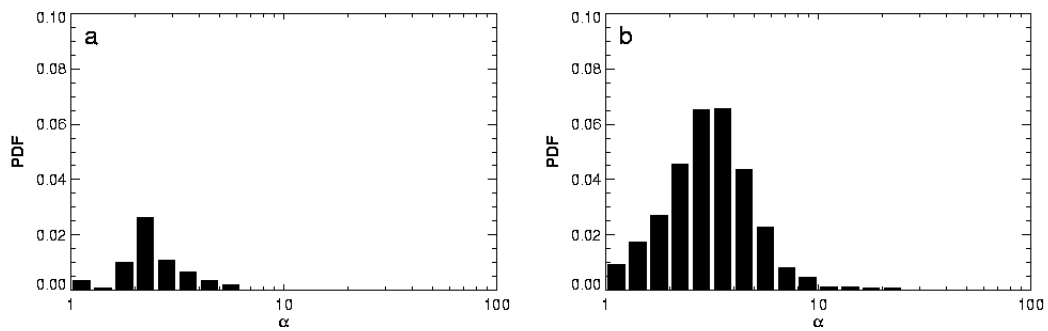


Figure 3. The spread of measured values of  $\alpha$  in two temperature intervals. (a)  $-55$  to  $-45^{\circ}\text{C}$  (b)  $-85$  to  $-75^{\circ}\text{C}$ .

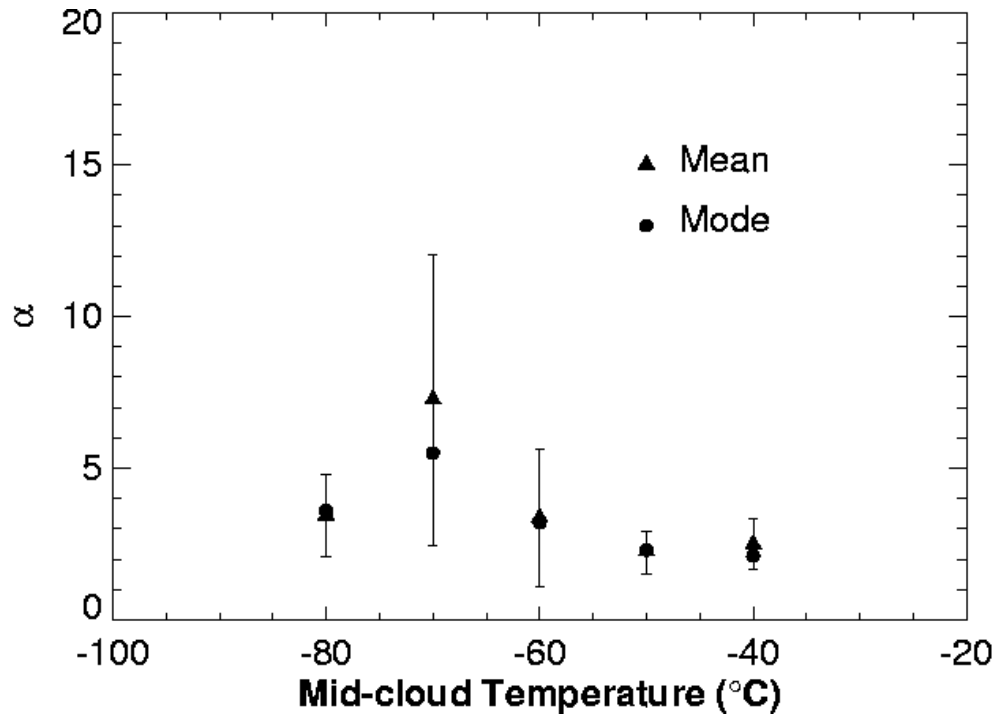


Figure 4. Plot of  $\alpha$  versus temperature for mode and average values as shown for ten-degree temperature intervals.

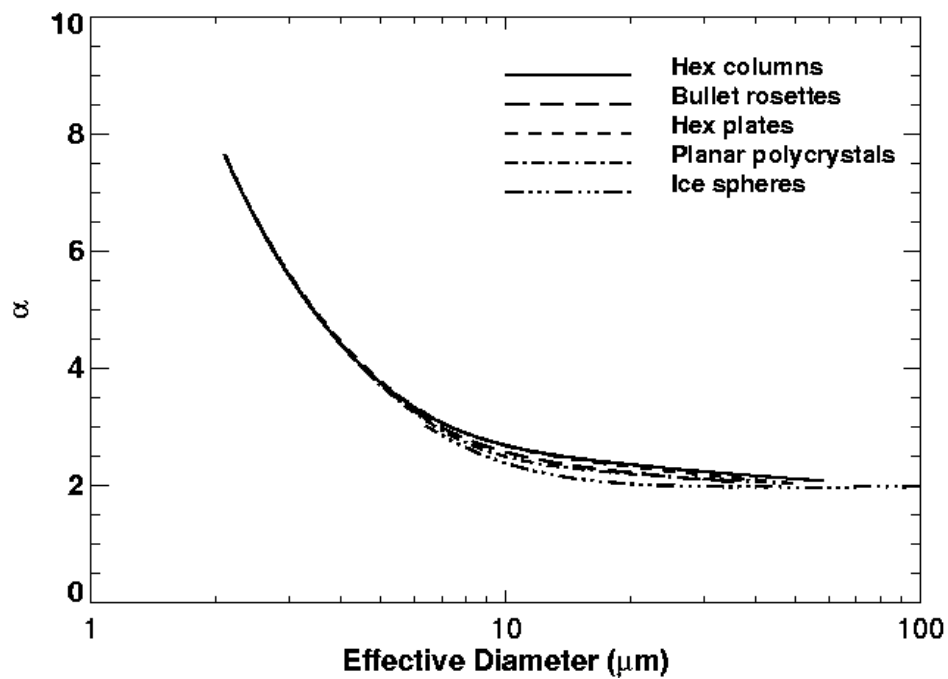


Figure 5. Plot of  $\alpha$  versus effective diameter  $D_e$  for several ice crystal habits (after Mitchell et al. 1996).

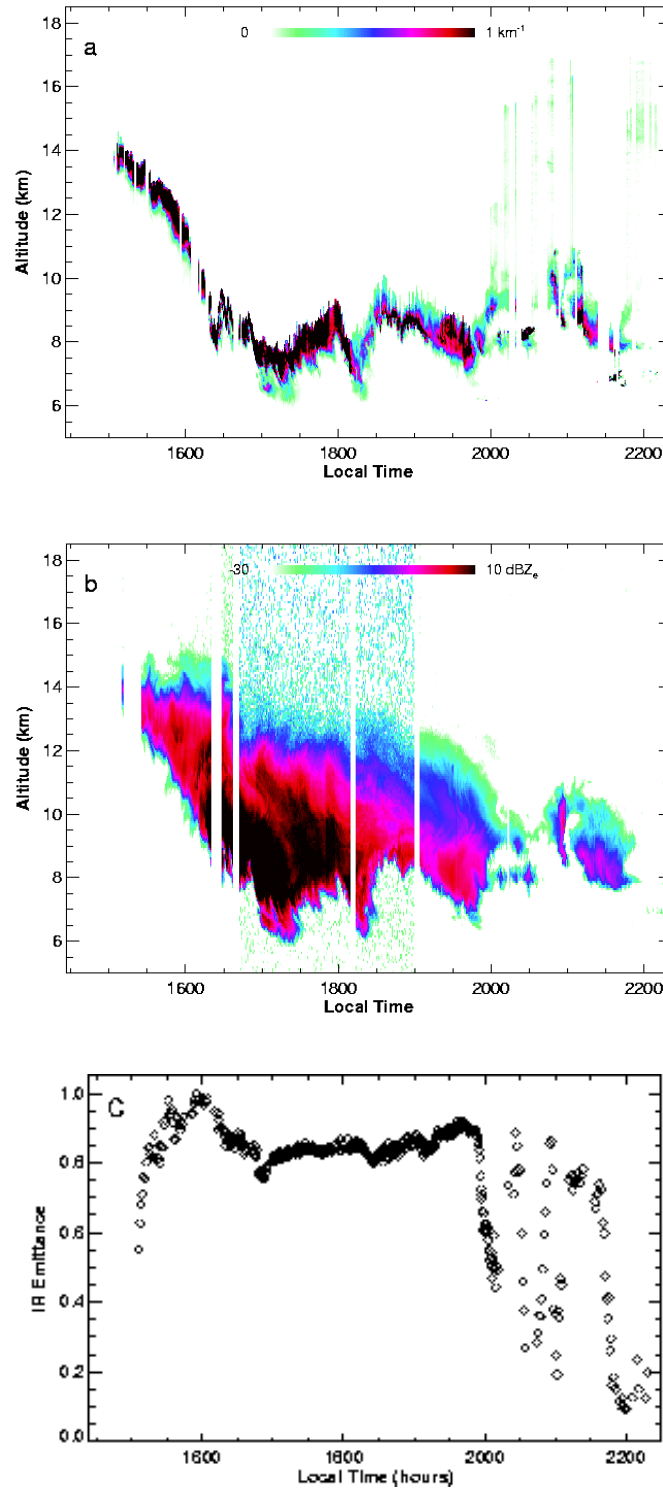


Figure 6. (a) Lidar time-height image of attenuated backscatter (532 nm) from a dissipating storm anvil, November 27. (b) Radar time-height image of reflectivity (33 GHz) for the same cloud. (c) Corresponding infrared emittance.

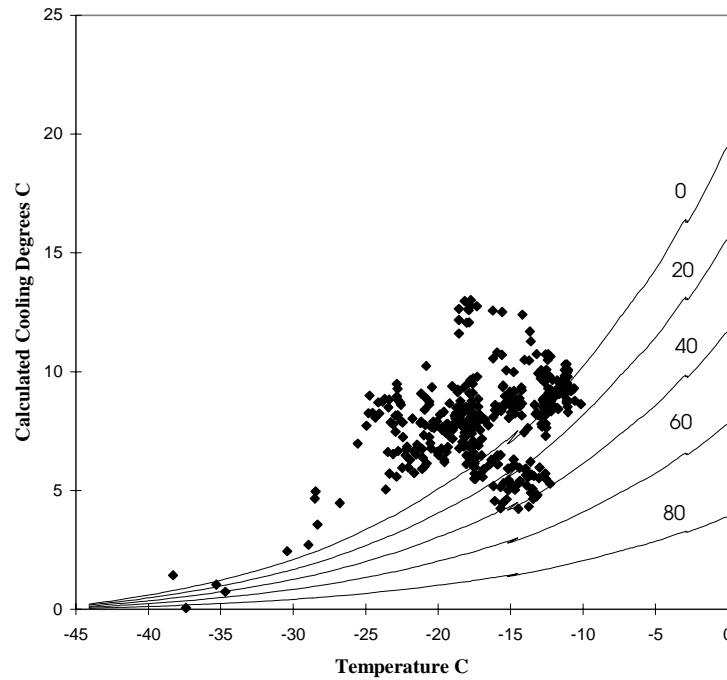


Figure 7. (a) Observed values of cloud base cooling  $\Delta T_m$ , plotted against time for anvil of 27 November.

(b) Calculated values of cloud base cooling,  $\Delta T$ , for various conditions of cloud base temperature and atmospheric humidity below cloud base (full lines). (Values were calculated from radiosonde data recorded at 1158 LT, before the advent of the anvil, 27 November 1995.) Observed values of cloud base cooling,  $\Delta T_m$ , for various cloud base temperatures are shown as single points.

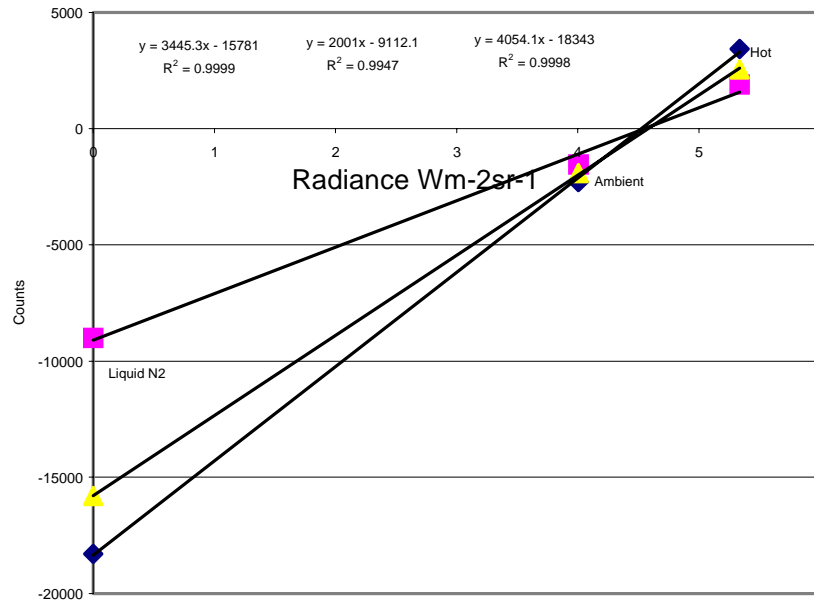


Figure 8. Three-point radiometer calibration counts versus radiance (gain 4, iris 100, 1 second).

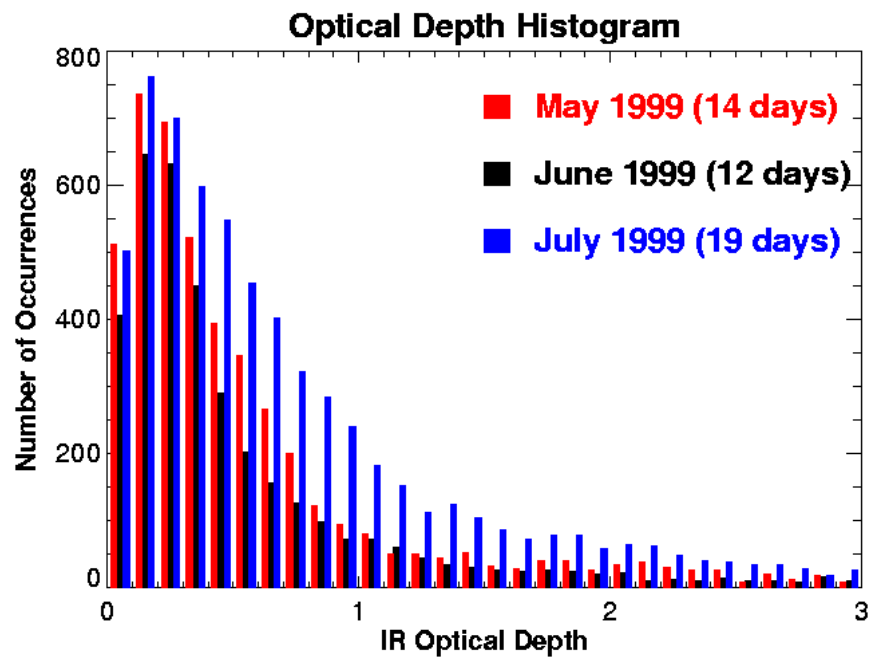


Figure 9. Optical depth histogram of clouds above 9 km during nighttime periods from observable days at Nauru during three months in 1999, calculated using LIRAD analysis of micropulse lidar and infrared radiometer data.

## **7. Refereed Publications Acknowledging this Research Grant**

Platt, C. M. R., S. A. Young, R. T. Austin, and G. R. Patterson, 2000a: LIRAD observations of tropical cirrus clouds in MCTEX. Part I: Optical properties and parameterisation of tropical cirrus, submitted to *J. Atmos. Sci.*

Platt, C. M. R., R. T. Austin, S. A. Young, and D. L. Mitchell, 2000b: LIRAD observations of tropical cirrus clouds in MCTEX. Part II: Detection of small particles in cold cirrus clouds, submitted to *J. Atmos. Sci.*

Platt, C. M. R., R. T. Austin, S. A. Young, and A. J. Heymsfield, 2000c: LIRAD observations of tropical cirrus clouds in MCTEX. Part III: Optical properties and base-cooling in dissipating storm anvil clouds, submitted to *J. Atmos. Sci.*

Young, S. A., C. M. R. Platt, R. T. Austin, and G. R. Patterson, 2000: Optical properties and phase of some midlatitude, midlevel clouds in ECLIPS, *J. Appl. Meteor.*, **39**, 135-153.

## **8. Extended Abstracts Acknowledging this Research Grant**

Platt, C. M. R., R. T. Austin, S. A. Young, A. J. Heymsfield, and S. M. Sekelsky, 2000d: Remote Radiometric Observation of Tropical Storm Anvil Base Temperature and Implications for Strong Evaporative Cooling, *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 13-17, 2000, San Antonio, Texas.*

Austin, R. T., C. Mitrescu, and G. L. Stephens, 2000: LIRAD Analysis of TWP Cirrus at Nauru, *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting, March 13-17, 2000, San Antonio, Texas.*

## **9. Status of submitted publications from the previous FY progress report.**

Young, S. A., C. M. R. Platt, R. T. Austin, and G. R. Patterson, 2000: Optical properties and phase of some midlatitude, midlevel clouds in ECLIPS, *J. Appl. Meteor.*, **39**, 135-153.